ARL-TR-7263 ● APR 2015

US Army Research Laboratory

Investigation of the Kinetic Energy Characterization of Advanced Ceramics

by Tyrone L Jones

NOTICES (12 pt)

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Investigation of the Kinetic Energy Characterization of Advanced Ceramics

by Tyrone L Jones
Weapons and Materials Research Directorate, ARL

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14. ABSTRACT

The US Army Research Laboratory conducted an initial study to characterize the material properties and armor performance of low-density ceramic composite tiles manufactured by the Ukrainian National Academy of Science, under a US Army International Technology Center contract. These ceramic formulations were compared with standard armor-grade boron carbide and silicon carbide tiles versus the 12.7-mm armor-piercing APM2 projectile.

15. SUBJECT TERMS

advanced ceramic, armor, B_4C, SiC, ballistic evaluation

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1. Introduction

Boron carbide (B_4C) is an attractive ceramic to the armor community because of its ability to fracture armor-piercing (AP) bullets and its low areal density. B_4C is one of the most mass-efficient ceramics against hard core bullets that are 12.5 mm in diameter and smaller.[1] The volumetric mass density (2.49 g/cc), compressive strength (3,070 MPa), and hardness (25.5 GPa, Knoop 1,000-gm test) of B_4C are attractive material properties compared with most advanced ceramics.[2] The Ukrainian National Academy of Science (NAS) manufactured ceramic composite tiles that were designed to fall within the density range of standard B_4C and silicon carbide (SiC) armor tiles, as shown in Fig. 1. The B_4C and SiC materials were manufactured by CoorsTek in the United States and were processed using pressure-assisted densification (PAD), while the NAS ceramics were processed using sintering methods. The nominal dimensions of these ceramic tiles were 90 × 90 mm and 8 mm thick. The material properties of each ceramic tile formulation were measured by the US Army Research Laboratory's (ARL's) Ceramics and Transparent Materials Branch.[3]

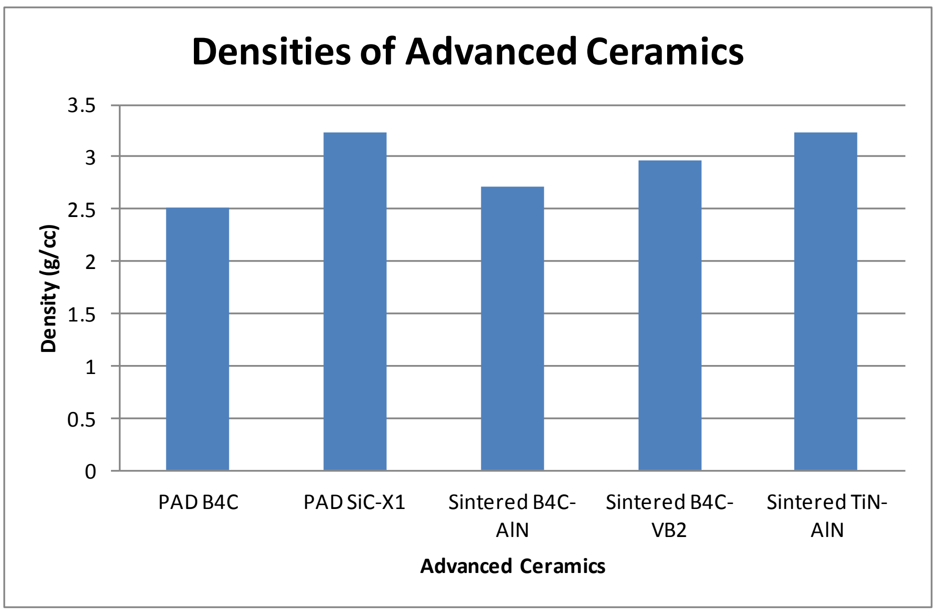
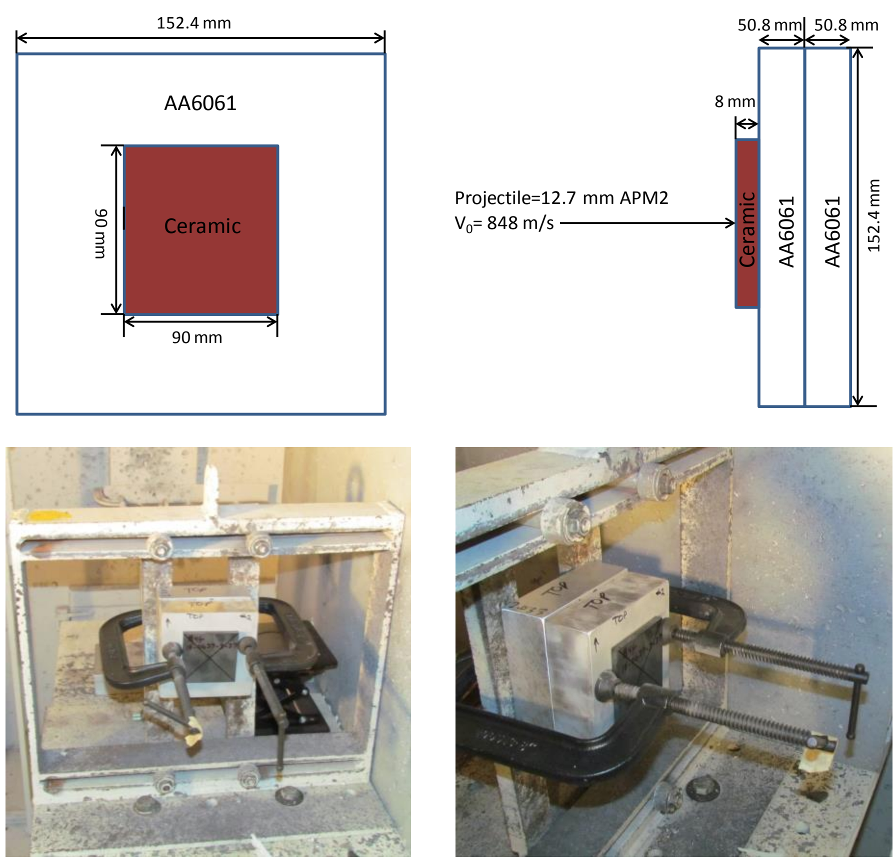


Fig. 1 Ceramic densities

2. Experimental Methodology

Depth of penetration (DOP) or residual penetration experiments were designed to determine the relative ballistic performance of different ceramic materials.[4] For DOP testing, a projectile is fired into a ceramic tile attached to a thick metal backer plate so that the projectile will not deform the back surface of the metal plate. These experiments avoid the fundamental problem of V_{50} ballistic dependence on armor design (e.g., front-to-back plate ratio and material), require fewer shots than V_{50} tests, and have a sensitivity equivalent to that of other ballistic test methods. The change in penetration into the metal plates provides a comparison with which to rank the performance of the ceramic materials.

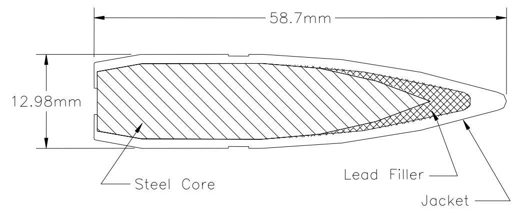
The target configuration used for these experiments is illustrated in Fig. 2. The target consisted of a 90- × 90-mm ceramic tile 8 mm thick backed by 2 backup plates of aluminum (Al) alloy 6061 (AA6061, MIL-DTL-32262[5]) plates 50.8 mm (2 inches) thick. An epoxy resin, Dureflex Optical Aliphatic Polyether Polyurethane Grade A4700, was used to attach each tile to the first 50.8-mm (2-inch) plate. AA6061 was chosen as a well-characterized and readily available backer material. The Al backer plates were also expected to provide better resolution than steel plates. No cover plate was employed.



(a) Front view (b) Side view

Fig. 2 Ceramic DOP target assembly

All ballistic impact experiments (sample size n = 3 per ceramic composite) were conducted at ARL. The test projectile includes a hardened steel core penetrator 47.6 mm (1.875 inches) long, a diameter of 10.87 mm (0.428 inch), and an aspect ratio of 4. It is known as the 12.7-mm APM2, shown in Fig. 3. The nominal projectile weight was 46 g, and the core density was 7.85 g/cc.



12.7-mm APM2

Projectile = 45.9 g

Hardened Steel Core = 25.9 g

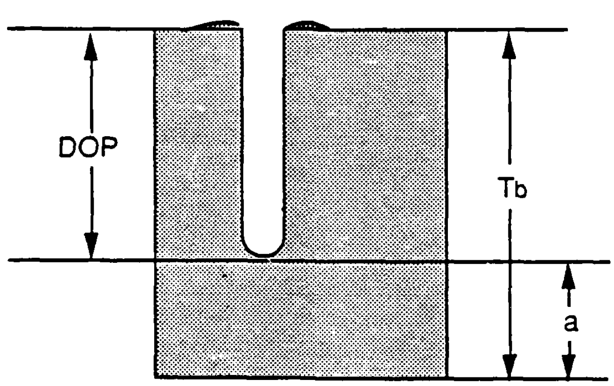
Rc = 60-65

Fig. 3 Cross section of a 12.7-mm APM2

The impact velocity used for all experiments was nominally 848 m/s (2,782 ft/s), although some shots were varied from 824 m/s (2,704 ft/s) up to 872 m/s (2,861 ft/s) into the Al back plates alone to provide for DOP corrections for velocity variations. The velocity was chosen to produce a range of practical residual penetrations while being consistent with normal operating conditions.

Projectiles with 3° or greater of total yaw were excluded from analysis, as previous studies had indicated this as an appropriate cutoff point for ballistic tests at zero obliquity.[4] Measuring the projectile yaw and velocity was accomplished using a Hewlett-Packard 150 kV Flash X-ray System in 2 orthogonal planes

All residual penetration measurements were obtained by sectioning the AA6061 plates. A band saw was used to section all penetration cavities, and measurements were made using vernier calipers to the deepest portion at the cavity, as indicated in Fig. 4. Measurement of the "a" value avoids errors that could be caused by deformation of the Al block around the entrance cavity.



$$DOP = T_b - a$$

Fig. 4 Measurement of residual penetration[4]

3. Results and Discussion

3.1 Aluminum Performance Baseline

To provide baseline data for residual penetration into the AA6061 backup plates, a few shots were fired over the velocity range from 824 to 872 m/s (2,704 to 2,871 ft/s), as shown in Table 1. The primary penetrator defeat mechanism, deceleration, appeared consistent over the velocity regime, yielding singular failure modes. Residual penetration values were then measured and plotted as a function of striking velocity to produce a baseline curve, as shown in Fig. 5.

Table 1 Front photos of reference material

<table>
<tr><th>$V_{x\text{-}ray}$
(m/s)</th><th>Plate 1
(front plate)</th><th>Plate 2</th></tr>
<tr><td>848</td><td>
</td><td>
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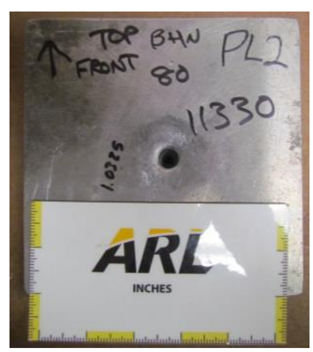
<tr><td>824</td><td>
</td><td>
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Table 1   Front photos of reference material (continued)

$V_{x\text{-}ray}$ (m/s)	Plate 1 (front plate)	Plate 2
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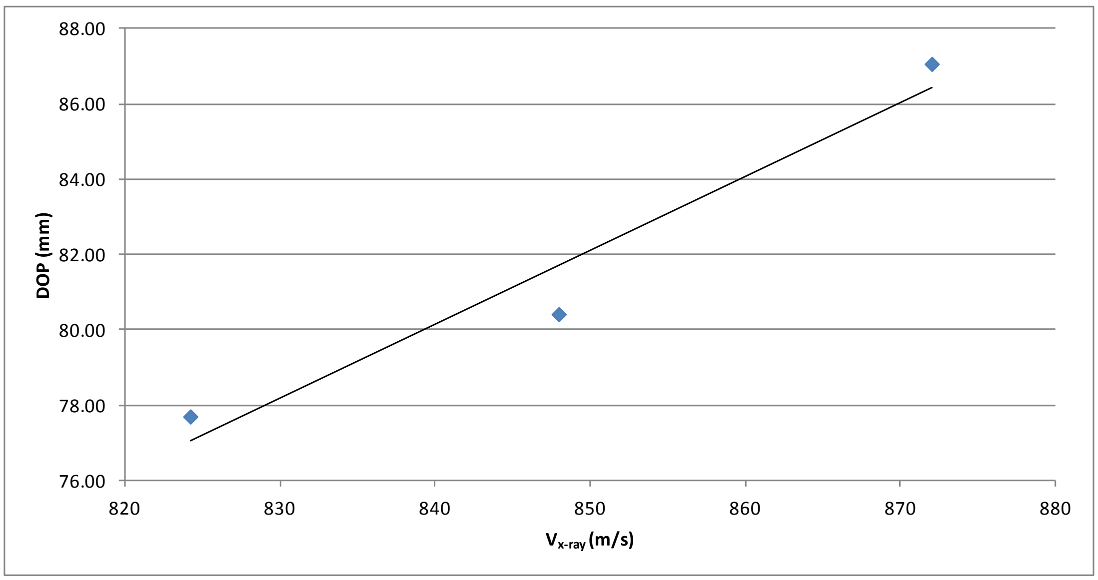

Fig. 5   AA6061 vs. 12.7-mm APM2

A linear regression of the reference data yielded the following equation:

$$DOP = 0.1959 * V_{x\text{-}ray} - 84.406. \quad (1)$$

The square of the correlation coefficient, R^2, is 0.946, indicating that this curve is a reasonable approximation. For example, an experimental impact velocity of 848 m/s would result in a DOP of 81.72 mm. The complete compilation of the data is shown in Appendix A.

3.2 Ceramic Inspection

A variety of different ceramics were evaluated. Ceramics tested included: PAD B_4C from CoorsTek, PAD SiC (SiC-X1) from CoorsTek, and sintered B_4C/Al nitride (B_4C-AlN), sintered B_4C/vanadium diboride (B_4C-VB_2), and sintered titanium nitride/AlN (TiN-AlN) from NAS. The PAD B_4C and PAD SiC are commercially available US armor ceramics that were used to establish baseline performance.

Ceramic target assemblies, as previously described, were fabricated for all materials listed. In general, 3 tiles of equal thickness (or areal density) were evaluated for each material. To adjust for variations in the actual strike velocity, all residual penetration values were normalized to a striking velocity of 848 m/s by means of the empirical fit shown in Eq. 1. The correction is made as follows: corrected DOP = measured DOP + [0.1959 * (848-$V_{x\text{-}ray}$)]. This technique has been found to be valid provided that a significant amount of the penetrator reaches the backup plate, the correction is relatively small, and the penetrator-defeat mechanism has not changed significantly with velocity. In support of this assumption, observations of the size and shape of the impact show no significant differences in penetrator cavity for impact velocity variations. Ceramic target failure will be examined in the next section. The complete compilation of the data is shown in Appendixes B–F.

3.3 Boron Carbide

Data was obtained for PAD B_4C at a thickness of 8 mm. The results of these experiments are shown in Fig. 6.

Fig. 6 B_4C vs. 12.7-mm APM2

The average density of the B_4C tiles evaluated was 2.52 g/cc, the average DOP was 28.16 mm, and the standard deviation was 0.26 mm. The features from the B_4C impact served as a reference for the ceramic variants.

3.4 Silicon Carbide

Data was obtained for PAD SiC-X1 at a thickness of 8 mm. The results of these experiments are shown in Fig. 7.

Fig. 7 SiC vs. 12.7-mm APM2

The average density of the SiC-X1 tiles evaluated was 3.23 g/cc, the average DOP was 14.56 mm, and the standard deviation was 2.83 mm, showing greater scatter than for B_4C for the quantities shot.

3.5 Boron Carbide–Aluminum Nitride

Data was obtained for sintered B_4C-AlN at a thickness of 8 mm. The results of these experiments are shown in Fig. 8.

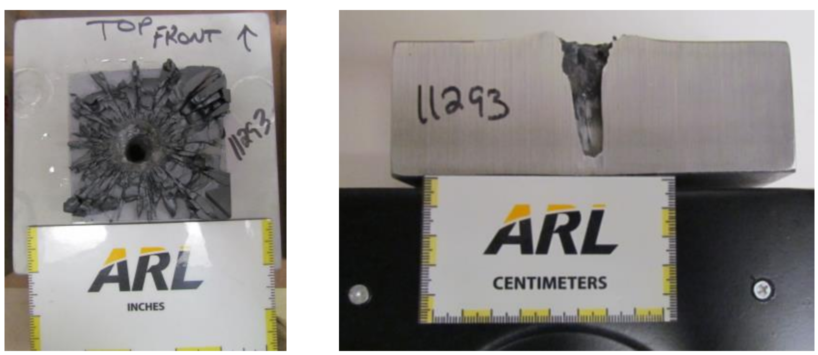

Fig. 8 B_4C-AlN vs. 12.7mm APM2

The average density of the B_4C-AlN tiles evaluated was 2.71 g/cc. The average DOP of this data was 42.83 mm. The standard deviation was 3.98 mm, showing greater scatter than for either B_4C tiles or SiC-X1 tiles.

3.6 Boron Carbide–Vanadium Diboride

Data was obtained for B_4C-VB_2 at a thickness of 8 mm. The results of these experiments are shown in Fig. 9.

Fig. 9 B$_4$C-VB$_2$ vs. 12.7-mm APM2

The average density of the B$_4$C-VB$_2$ tiles evaluated was 2.97 g/cc, the average DOP of this data was 26.36 mm. The standard deviation was 2.69 mm, showing greater scatter than the B$_4$C tiles but equal to the SiC-X1 tiles.

3.7 Titanium Nitride–Aluminum Nitride

Data was obtained for sintered TiN-AlN at a thickness of 8 mm. The results of these experiments are shown in Fig. 10.

Fig. 10 TiN-AlN vs. 12.7-mm APM2

The average density of the TiN-AlN tiles evaluated was 3.73 g/cc, the average DOP was 16.32 mm, and the standard deviation was 0.33 mm, equal to the scatter of the B$_4$C tiles and lower than the scatter of the SiC-X1.

3.8 Comparative Performance of Ceramics

Since AA6061 was the reference material used in this study, Eq. 2 was used to provide a coefficient of performance (C_p) of the ceramics compared with the reference material:

$$C_p = (\rho_{AA6061}) \frac{DOP_{Base\_AA6061} - DOP_{Corr\_AA6061}}{AD_{Ceramic}}, \tag{2}$$

where DOP_{Base_AA6061} is the average expected residual DOP into bare Al at 848 m/s. DOP_{Corr_AA6061} is the residual DOP into AA6061 after perforating the ceramic tile, corrected for the variations in striking velocity. The calculated C_p value provides a relative comparison of the ceramic to AA6061, i.e., a C_p of 5 means the ceramic is 5 times more weight effective than AA6061. The calculated ceramic C_p's are shown in Table 2, and a ceramic performance map is illustrated in Fig. 11.

Table 2 Comparative performance of ceramics based on C_p

Experiment No.	B_4C	SiC-X1	B_4C-AlN	B_4C-VB_2	TiN-AlN
1	7.11	6.76	4.45	6.82	6.84
2	7.03	6.79	5.06	6.64	5.94
3	7.07	7.27	4.83	6.79	6.20

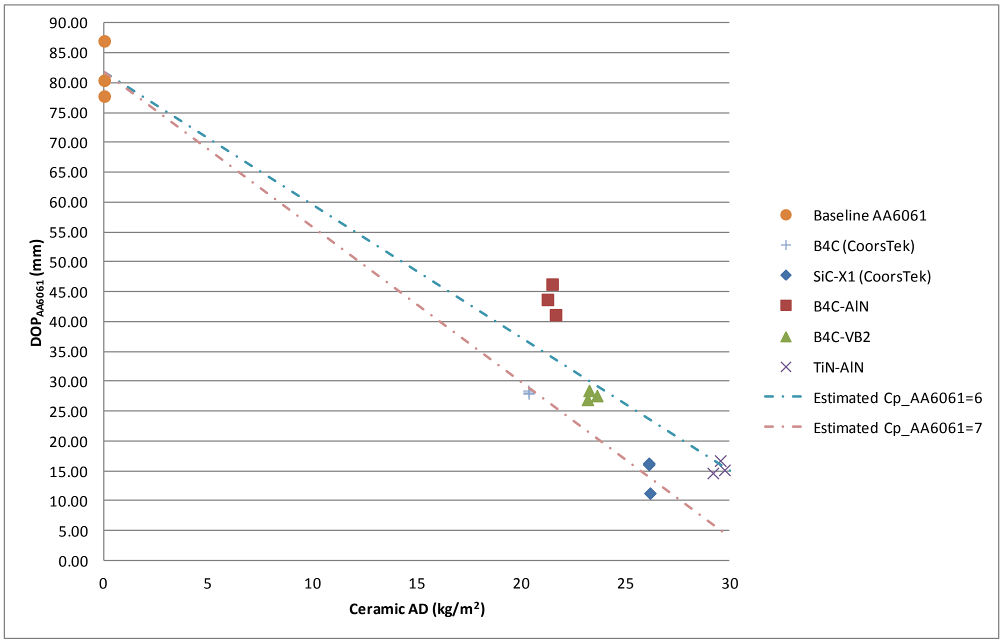

Fig. 11 Ceramic performance map

The baseline CoorsTek B_4C and SiC-X1 tiles provided the highest comparative performance based on C_p. The performance of the sintered ceramics was less than the PAD B_4C or PAD SiC materials. It is unclear if any future improvements can be made in the composition or processing of the sintered tiles that might improve performance. The B_4C-AlN provided the lowest performance and is probably the formulation least likely to undergo any follow up efforts.

4. Conclusions

From the ballistic data and analysis, the AA6061 proved to be an adequate material as a backup block for DOP testing of the various ceramics under ballistic impact. The ranking of the ceramic tiles, in decreasing order based on comparing C_p values, is as follows:

1. B_4C
2. SiC
3. B_4C-VB_2
4. TiN-AlN
5. B_4C-AlN

Opportunities for future investigation include the following:

- Expand the parametric analysis of ballistic performance to include the effect of varying armor piercing projectile diameters, i.e., 0.30-cal. APM2.
- Expand the projectile target mapping to provide a more extensive view of more performance regions, i.e., different velocity regimes.
- Determine if improvements can be made in the composition or processing of the sintered tiles.

5. References

1. Laible R, editor. Ballistic materials and penetration mechanics. New York: Elsevier Scientific Publishing Co; 1980.

2. CoorsTek. Material Technology Guide. [accessed 2013]. http://www.coorstek.com/resource-library/library/8510-091_ceramic_armor.pdf.

3. Swab J. Investigation of the material characterization of armor ceramics from the Ukraine. In development; 2015.

4. Woolsey P, Kokidko D, Mariano S. Alternative test methodology for ballistic performance ranking of armor ceramics. Watertown (MA): Army Materials Technology Laboratory (US); 1989.

5. MIL-DTL-32262. Armor plate, aluminum alloy, unweldable applique 6061; Aberdeen Proving Ground (MD): Army Research Laboratory (US); 2007 Jul.

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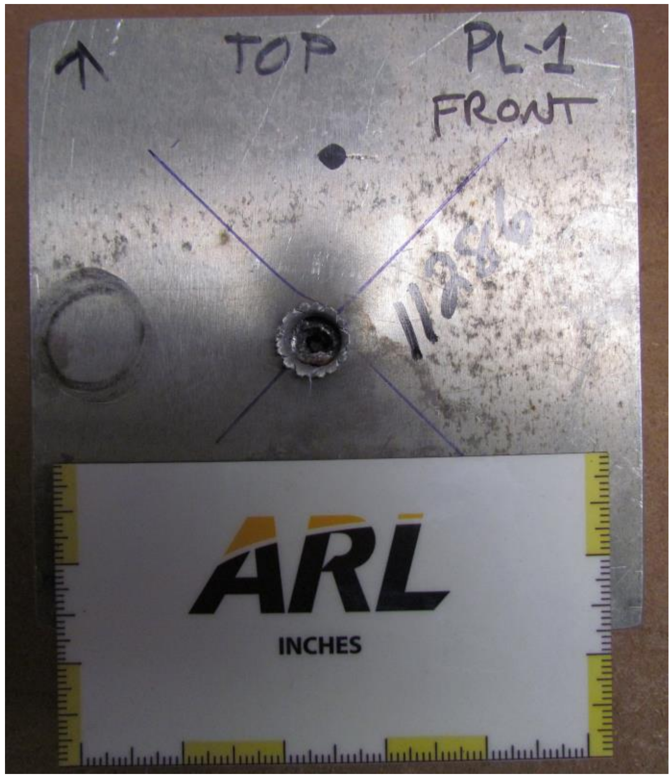
Appendix A. Baseline Ballistic Data

This appendix appears in its original form, without editorial change.

US/Ukraine Armor Ceramic Development Program							**Date:**	1/9/2013
Carrier:		AA6061						
Lateral:		6.0x6.0	inches					
Thickness:		Plate 1:		inches	Plate 2:		inches	
Hardness:		Plate 1:	101	HBN	Plate 2:	97	HBN	
ρ_{AA6061}:		2.70	g/cc					
Projectile:		See Comments			**ρ_{AA6061}:**	2.7	g/cc	
Obliquity:		0°						
Target Velocity (V_{target}):			2782	ft/s	848	m/s		
		Plate 1	**Plate 2**					
Target	**Ceramic**	**AA6061**	**AA6061**	**V_{meas}**	**Total Yaw, γ**	**DOP_{meas}**	**Shot**	**Comments**
	AD_{meas}	**Thick**	**Thick**					
ID	kg/m2	mm	mm	m/s	degrees	mm	ID	
D	0	51.848	51.765	848	0.56	80.42	11286	0.50-cal APM2; Target Velocity
E	0	51.473	51.778	824	0.56	77.70	11330	0.50-cal APM2; Low Velocity for Correction Factor
F	0	51.556	51.797	872	0.56	87.06	11331	0.50-cal APM2; High Velocity for Correction Factor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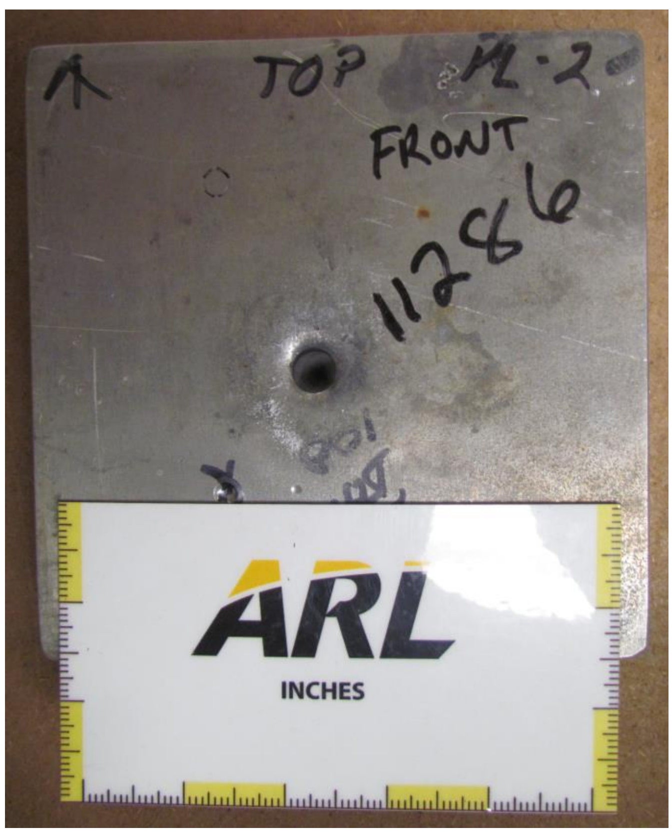
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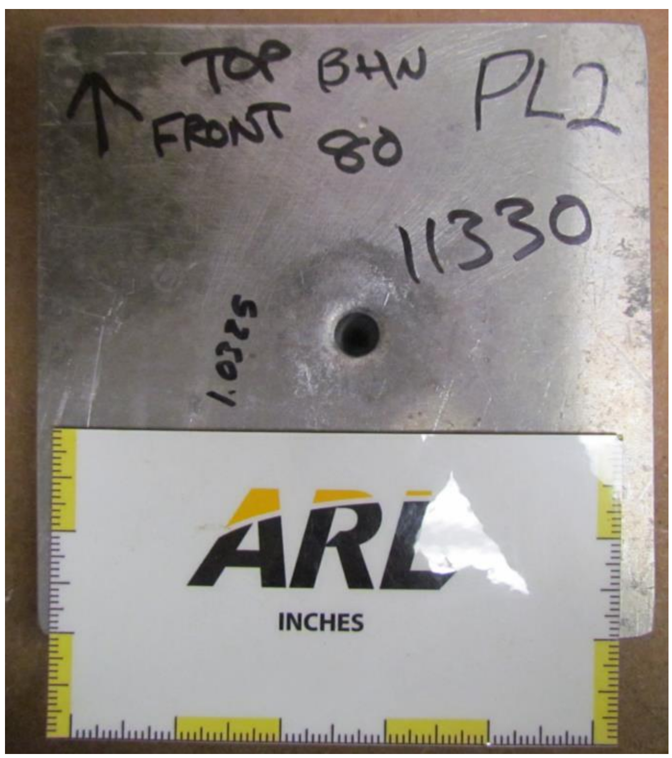
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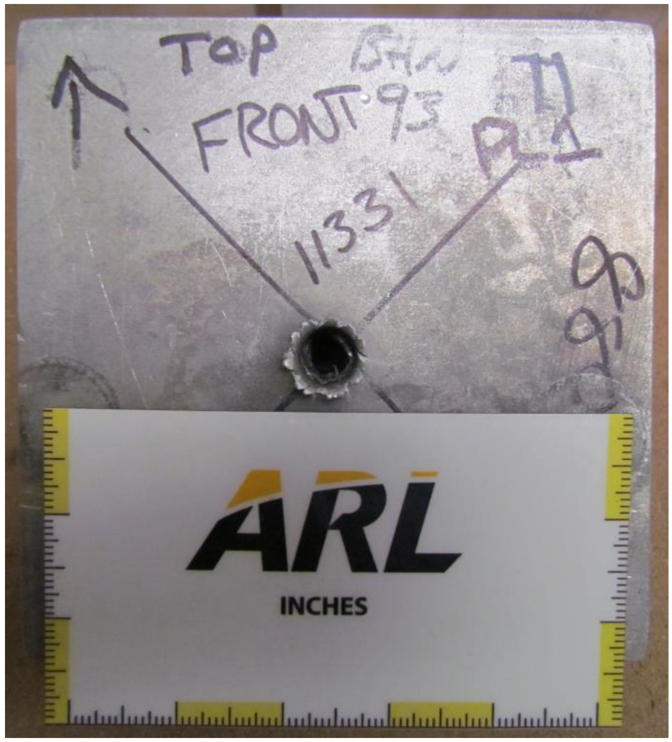
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Appendix B. B_4C Ceramic Data

This appendix appears in its original form, without editorial change.

US/Ukraine Armor Ceramic Development Program						**Date:**	1/9/2013			
Manufacturer:		CoorsTek								
Material:	B_4C			**LOWER BASELINE**						
Nominal Dimensions:			**Lateral:**	92.608x92.608	mm	3.464x3.464	inches			
			Thickness:	8.001	mm	0.315	inches			
Carrier:	AA6061		**Lateral:**	6.0x6.0	inches					
			Thickness:	2.00	inches					
Projectile:	See Comments									
Obliquity:	0°									
Target Velocity (V_{target}):		2782	ft/s	848	m/s					
		Plate 2								
B_4C on 2" thick AA6061	**ρ_{ARL}**	**AA6061 Thick**	**Ceramic AD_{meas}**	**V_{meas}**	**Total Yaw, γ**	**DOP_{meas}**	**DOP_{corr}**	**Shot**	**Comments**	**C_{p_AA6061}**
ID	g/cc	mm	kg/m^2	m/s	degrees	mm	mm	ID		
37	2.52	8.08	20.35	2786	0.90	28.35	28.11	11288	0.50-cal APM2	7.11
38	2.52	8.08	20.36	2799	0.50	28.96	27.94	11291	0.50-cal APM2	7.13
43	2.52	8.08	20.35	2804	1.25	29.76	28.44	11292	0.50-cal APM2	7.07


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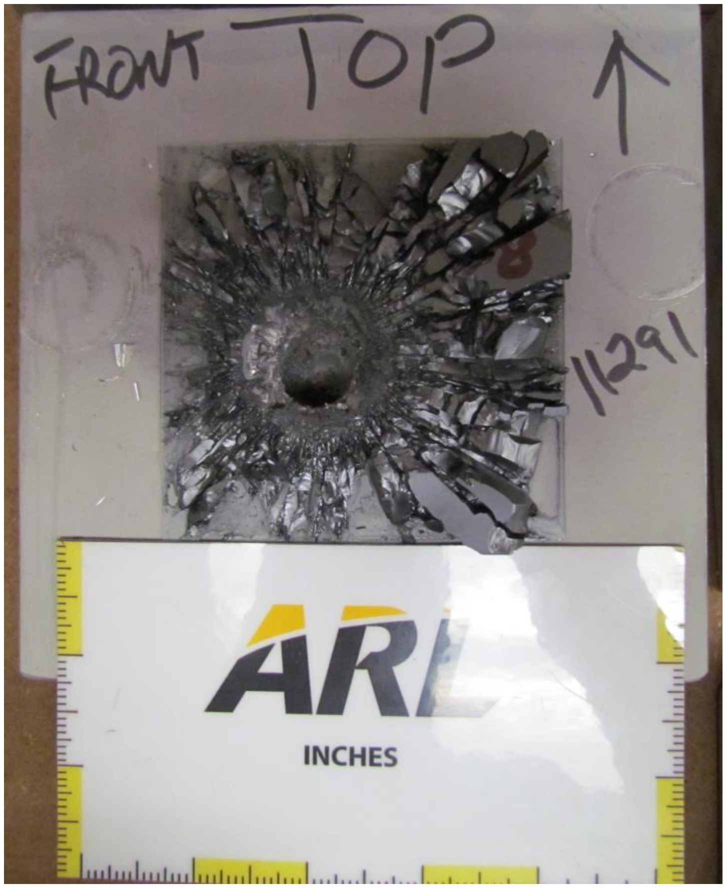
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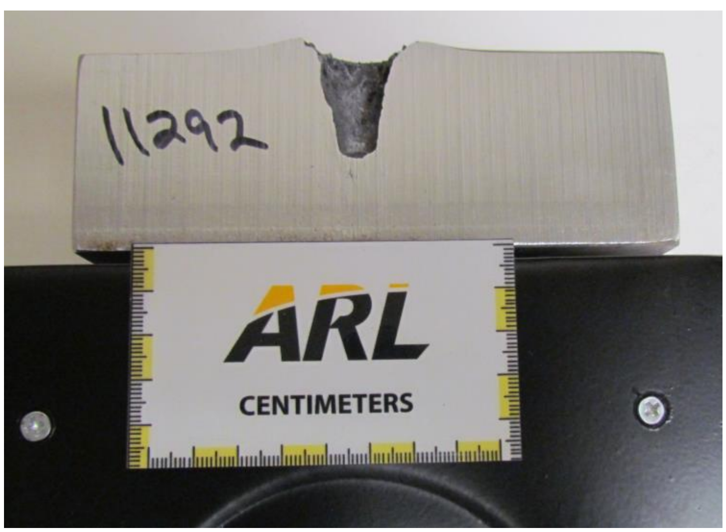
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Appendix C. SiC-X1 Ceramic Data

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US/Ukraine Armor Ceramic Development Program						**Date:**	1/9/2013			
Manufacturer:		CoorsTek								
Material:	SiC-X1			**UPPER BASELINE**						
Nominal Dimensions:			**Lateral:**	92.608x92.608	mm	3.464x3.464	inches			
			Thickness:	8.001	mm	0.315	inches			
Carrier:	AA6061		**Lateral:**	6.0x6.0	inches					
			Thickness:	2.00	inches					
Projectile:	See Comments									
Obliquity:	0°									
Target Velocity (V_{target}):		2782	ft/s	848	m/s					
		Plate 2								
SiC-X1 on 2" thick AA6061	ρ_{ARL}	**AA6061**	**Ceramic**	V_{meas}	**Total Yaw, γ**	DOP_{meas}	DOP_{corr}	**Shot**	**Comments**	C_{p_AA6061}
		Thick	AD_{meas}							
ID	g/cc	mm	kg/m^2	m/s	degrees	mm	mm	ID		
50	3.23	8.08	26.13	846	0.79	15.91	16.27	11287	0.50-cal APM2	6.76
53	3.23	8.08	26.12	860	0.90	18.40	16.07	11289	0.50-cal APM2	6.79
59	3.24	8.09	26.18	850	1.12	11.75	11.27	11290	0.50-cal APM2	7.27


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Appendix D. B_4C-AlN Ceramic Data

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US/Ukraine Armor Ceramic Development Program — **Date:** 3/2/2012

Manufacturer: Frantsevich Institute for Problems in Materials Science, National Academy of Sciences of Ukraine

Material: B_4C-AlN

Nominal Dimensions:	**Lateral:**	90.0x90.0	mm	3.50x3.50	inches
	Thickness:	8	mm	0.310	inches

Carrier:	AA6061	
Lateral:	6.0x6.0	inches
Thickness:	2.00	inches

Projectile: See Comments

Obliquity: 0°

Target Velocity (V_{target}): 2782 ft/s 848 m/s

B_4C-AlN on 2" thick AA6061	ρ_{ARL}	Plate 2 AA6061 Thick	Ceramic AD_{meas}	V_{meas}	Total Yaw, γ	DOP_{meas}	DOP_{corr}	Shot	Comments	C_{p_AA6061}
ID	g/cc	mm	kg/m^2	m/s	degrees	mm	mm	ID		
3	2.71	7.92	21.49	853	1.27	47.17	46.27	11293	0.50-cal APM2	4.45
11	2.73	7.92	21.65	839	0.75	39.36	41.15	11336	0.50-cal APM2	5.06
12	2.70	7.88	21.26	839	1.653	41.97	43.71	11337	0.50-cal APM2	4.83


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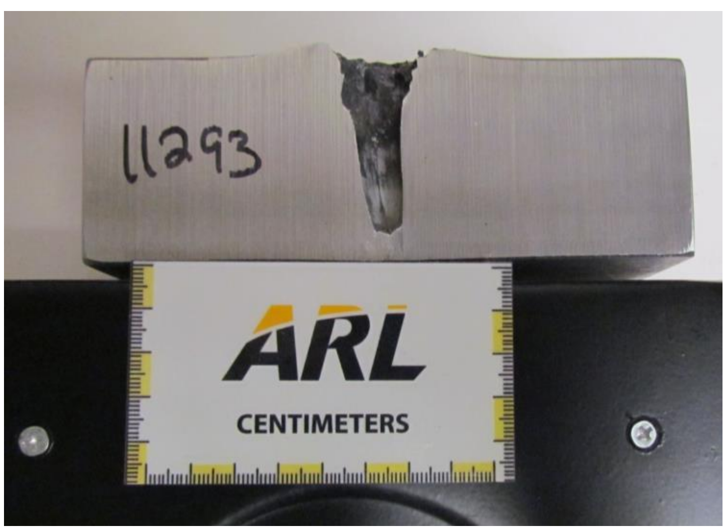
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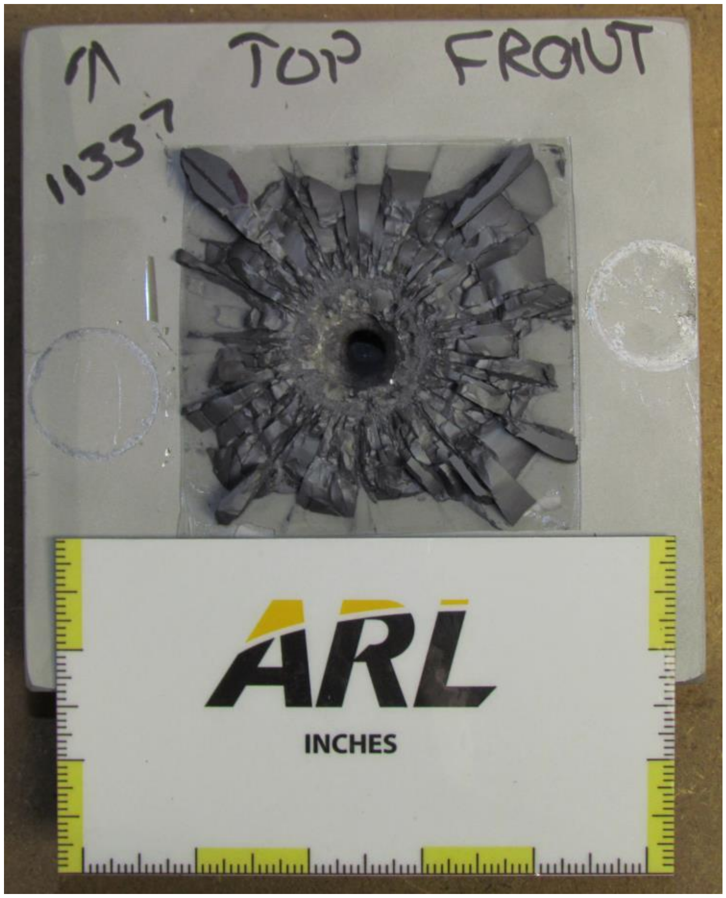
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Appendix E. B_4C-VB_2 Ceramic Data

This appendix appears in its original form, without editorial change.

US/Ukraine Armor Ceramic Development Program — **Date:** 3/2/2012

Manufacturer:		Frantsevich Institute for Problems in Materials Science, National Academy of Sciences of Ukraine								
Material:	B_4C-VB_2									
Nominal Dimensions:			**Lateral:**	90.0x90.0	mm	3.50x3.50	inches			
			Thickness:	8	mm	0.310	inches			
Carrier:	AA6061		**Lateral:**	6.0x6.0	inches					
			Thickness:	2.00	inches					
Projectile:	See Comments									
Obliquity:	0°									
Target Velocity (V_{target}):		2782	ft/s	848	m/s					
		Plate 2								
B_4C-AlN on 2" thick AA6061	**ρ_{ARL}**	**AA6061**	**Ceramic**	**V_{meas}**	**Total Yaw, γ**	**DOP_{meas}**	**DOP_{corr}**	**Shot**	**Comments**	**C_{p_AA6061}**
		Thick	**AD_{meas}**							
ID	g/cc	mm	kg/m^2	m/s	degrees	mm	mm	ID		
13	2.97	7.81	23.18	861	0.91	29.56	26.96	11294	0.50-cal APM2	6.82
15	2.97	7.96	23.64	833	0.25	24.68	27.60	11334	0.50-cal APM2	6.64
18	2.96	7.85	23.26	830	0.35	24.94	28.47	11335	0.50-cal APM2	6.79


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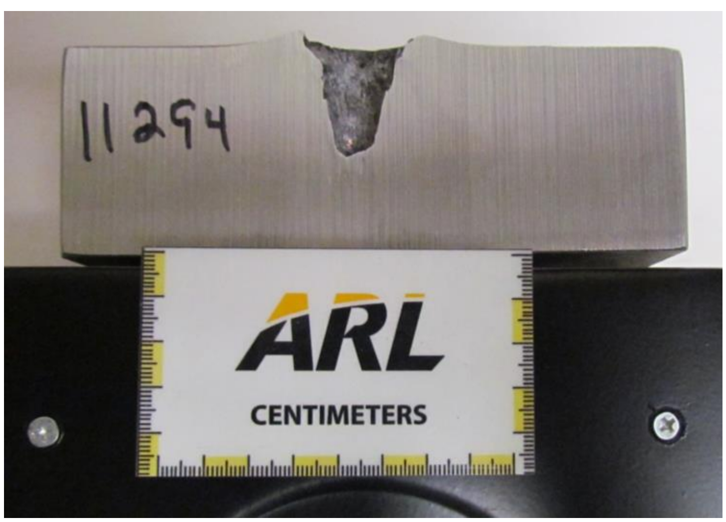
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Appendix F. TiN-AlN Ceramic Data

This appendix appears in its original form, without editorial change.

US/Ukraine Armor Ceramic Development Program **Date:** 3/2/2012

Manufacturer: Frantsevich Institute for Problems in Materials Science, National Academy of Sciences of Ukraine

Material: TiN-AlN

Nominal Dimensions:	**Lateral:**	90.0x90.0	mm	3.50x3.50	inches
	Thickness:	8	mm	0.310	inches
Carrier: AA6061	**Lateral:**	6.0x6.0	inches		
	Thickness:	2.00	inches		

Projectile: See Comments

Obliquity: 0°

Target Velocity (V_{target}): 2782 ft/s 848 m/s

TiN-AlN on 2" thick AA6061	**ρ_{ARL}**	**Plate 2 AA6061 Thick**	**Ceramic AD_{meas}**	**V_{meas}**	**Total Yaw, γ**	**DOP_{meas}**	**DOP_{corr}**	**Shot**	**Comments**	**C_{p_AA6061}**
ID	g/cc	mm	kg/m^2	m/s	degrees	mm	mm	ID		
28	3.75	7.91	29.75	855	1.00	16.54	15.16	11295	0.50-cal APM2	6.84
29	3.76	7.87	29.55	844	0.25	15.939	16.71	11332	0.50-cal APM2	5.94
31	3.66	7.97	29.2	857	0.5	16.485	14.63	11333	0.50-cal APM2	6.20


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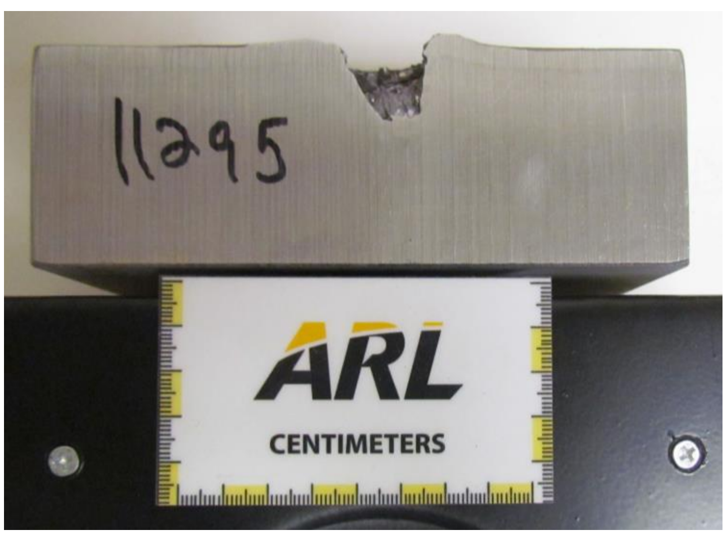
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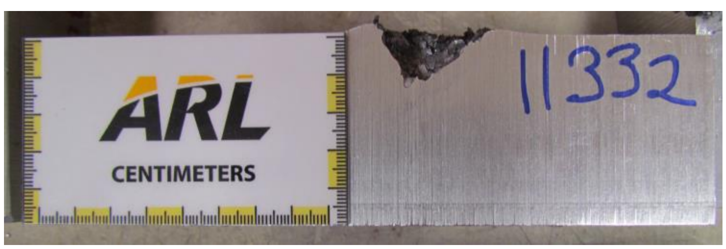
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List of Symbols, Abbreviations, and Acronyms

Al	aluminum
AlN	aluminum nitride
AP	armor-piercing
ARL	US Army Research Laboratory
B_4C	boron carbide
C_p	coefficient of performance
DOP	depth of penetration
NAS	National Academy of Science
PAD	pressure-assisted densification
SiC	silicon carbide
TiN	titanium nitride
VB_2	vanadium diboride

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